US CLIVAR Workshop on Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and sub-Arctic Seas
Seattle, 27-30 Jun 2022

# Synthesis of historical (and modern) observations through reanalysis: Successes and challenges


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# Vision of US CLIVAR workshop organizers:

1. **Assess our understanding** of the Arctic Ocean circulation and changes and **discuss observing system requirements** needed to confirm and extend that understanding

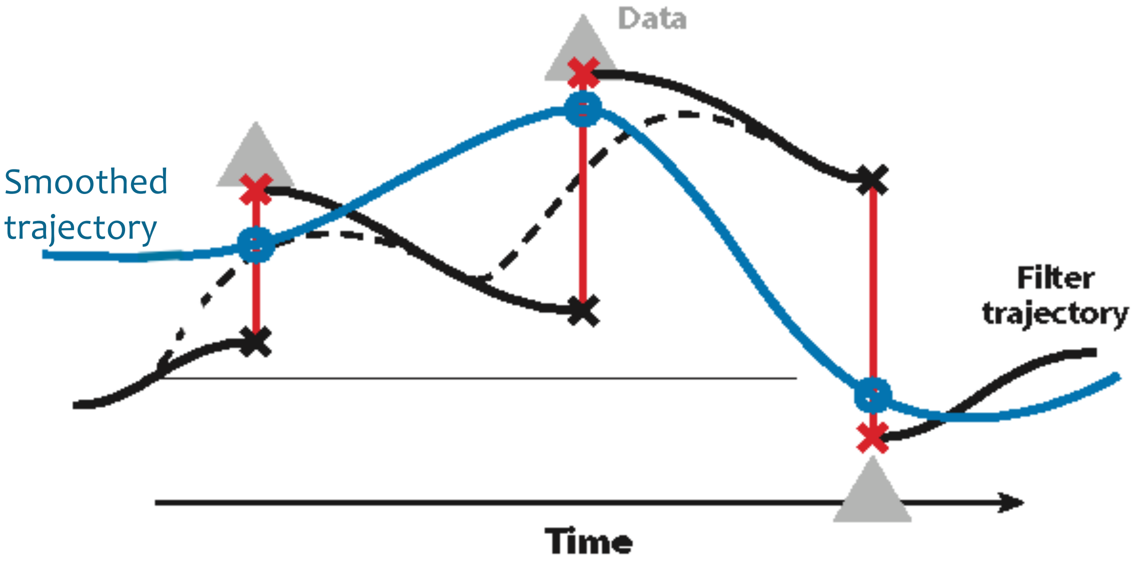
2. Explore changes in Arctic Ocean & sub-Arctic seas circulation related to global change and the observing system required **to track those changes;** cognizant of practical, geopolitical, & operational constraints;

3. **Experimental design & data assimilation; Feedbacks between model simulations/data assimilation ← → observational analyses**

# Identifying Scientific Goals ← → Methodology

1. understanding of the Arctic Ocean circulation;
2. changes in Arctic Ocean & sub-Arctic seas circulation

- Forecasting?
- Prediction/Projection?
- Climate research?
- Dynamical consistency?
- Budget closure?
- Uncertainty estimate?




Data Assimilation, Filter vs. Smoother

[Stammer et al., 2016]

# Examples of high-latitude ocean-sea ice reanalyses

- ASTE R1 (UT Austin, Nguyen et al., 2021)
- RARE (U. Maryland, Carton et al., in prep)
- TOPAZ4 (NERSC, Sakov et al., 2012)
- PIOMASS (U. Washington, Zhang & Rothrock 2003)

- ORAS5 (ECMWF, Zuo et al., 2018)
- SODA3 (U. Maryland, Carton et al., 2018)
- GECCO3 (Hamburg Univ., Köhl 2020)
- ECDA3 (GFDL/NOAA)
- Others (e.g., Uotila et al., 2018, An asessement of ten ocean reanalyses in the polar regions)

Atmospheric forcing:

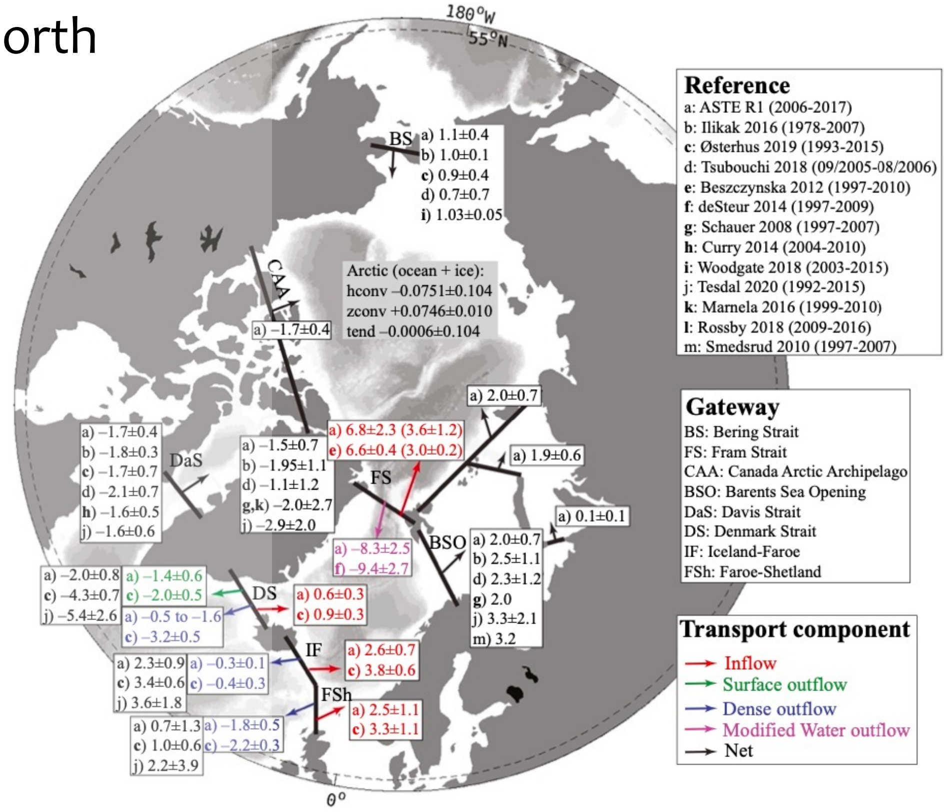
ERA-interim/ERA5
(CARRA)
MERRA2
JRA55
NCEP
CORE-II, others

# Arctic Subpolar gyre sTate Estimate (ASTE) Release 1



The first of its kind for Arctic & subpolar North Atlantic ocean-sea ice reanalysis:

- (multi-)decadal, for climate studies
- Fit to diverse > $10^9$ satellite & high-latitude in situ observations
- Model dynamics – interpolator where there is no data
- 4D-var non-sequential
  - → **Dynamically consistent**
  - → **Budget closures** for mass, heat, salt, momentum
- Accounts for **uncertain input parameters** (surface forcing, internal mixing, initial conditions)



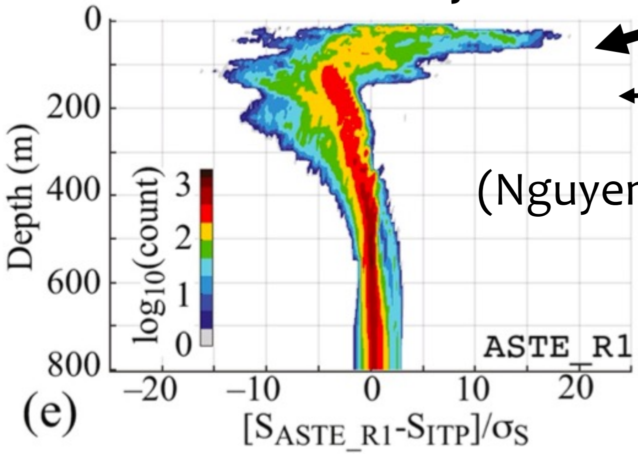

(Nguyen et al. 2021)

# ASTE Release 1: Observational constraints

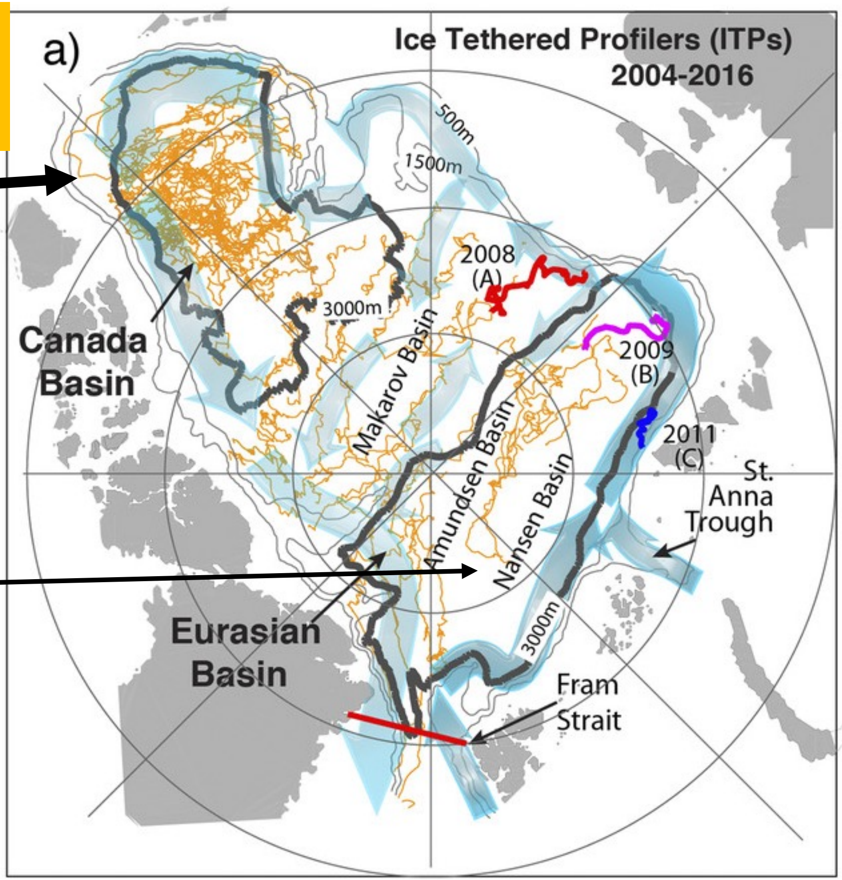
**ITP: crucial for subsurface T/S in W. Arctic**
**Fram Strait: crucial for volume & heat flux**

Observational density distribution:
→ non-unique ways to improve uncertain / highly unconstrained input parameters

→ Persistent reanalysis errors/biases




(Nguyen et al. 2021)

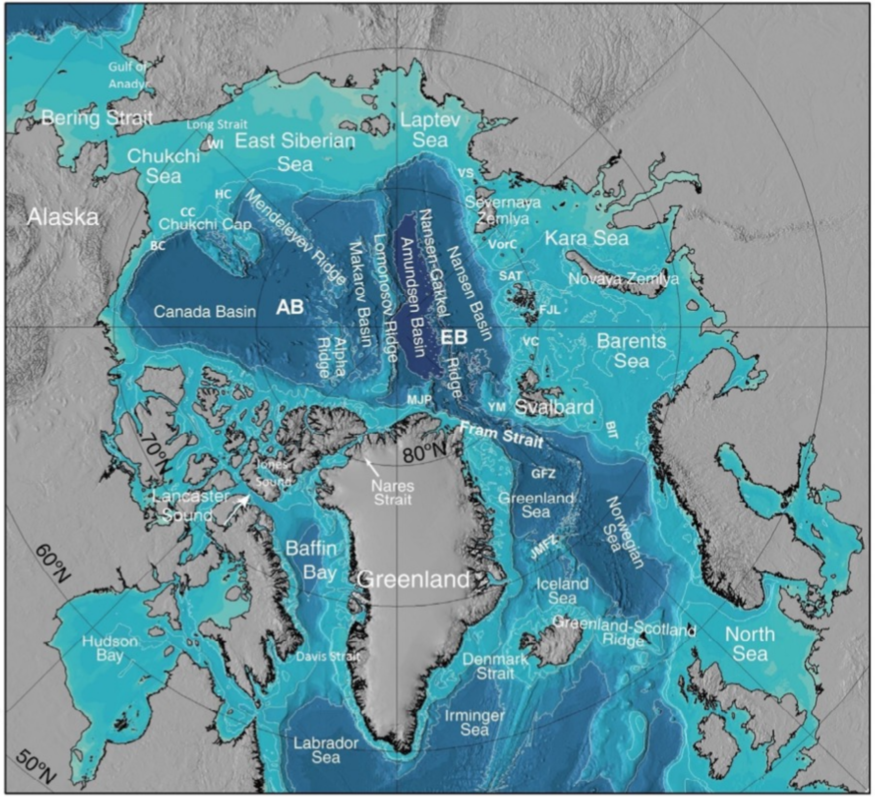



(Nguyen et al. 2020)

# Example: AW circulation: A priori information / Consensus

Observations:

- Nansen's Fram expedition 1893-1896, Nansen bottles T/S observations: ``This **warmer** and more **strongly saline water** must clearly originate from the .. Atlantic Ocean .., **flowing in a north and northeasterly** direction off Novaya Zemlya and .. Spitzbergen and then diving under the colder, but lighter and less briny, water of the Polar Sea, and filling up the depths of the polar basin."
- 1930s-1980s: Soviet & US & Canada drifting ice stations; 1990s: ice breakers; 2000s: ITPs
  → Hydrography, bathymetry, sea ice thickness and drifts
- 1990s-2000s: Mooring arrays Fram, Bering, Davis, BSO, NABOS, BGEP/BGOS
  → hydrography + currents, bathymetry




(sources & ref therein: Rudels 2018; Potemra 2003; Nansen 1897)

# Atlantic Water Circulation: inference

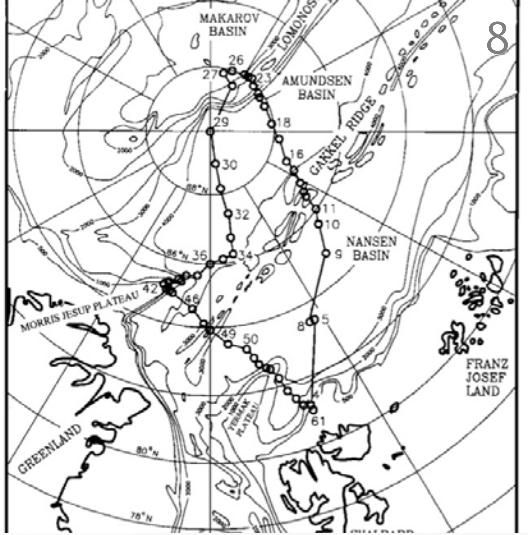
Rudels 2012; Tomofeyev 1960; Coachman & Barnes, 1963

**Cyclonic circulation:** "***deduced*** *from the decrease in temperature of the Atlantic core in the different parts of the Arctic Ocean*"

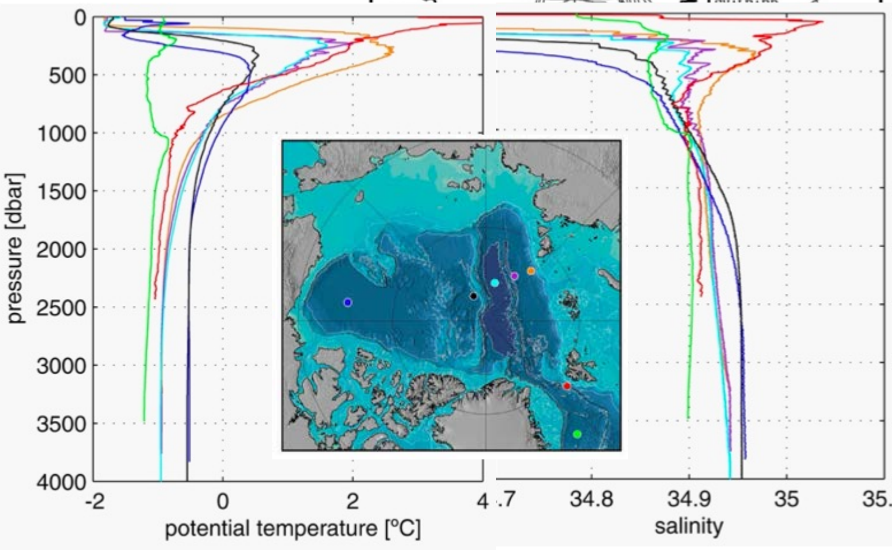
Highest: Nansen Basin N. of Svalbard
Lowest: Canada Basin & N. of Greenland
==> "***indicating***" a cyclonic flow

## Oden 1991:

- T fronts: over Gakkel & over Lomonosov ridges
- Intrusions of Fram & BSO branches in central part of basin → "***imply*** *a part of the boundary current leaves the continental slope and enters the interior Eurasian Basin, forming a return flow towards Fram Strait*"




Oden 1991 section
(Rudels 1994)

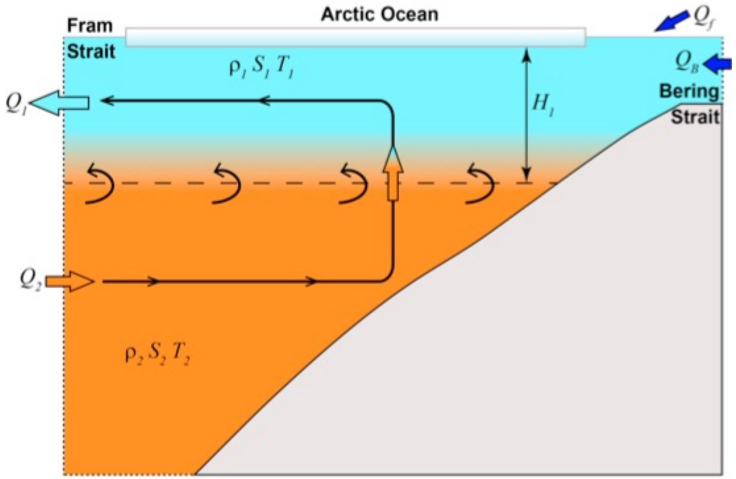


# Atlantic Water Circulation: theory

**Estuarine System** (Aagaard et al., 1985; Stigebrandt 1981; Rudels 1989; Eldevik & Nilsen, 2013):

- balance of horz in/outflow + vert entrainment

- **Reduced space, simplified geometry**
  - Invert for box-mean parameters




**Topostrophy**: (Holloway 1992, 2004)

- Lateral eddy momentum flux, eddy-topography interactions

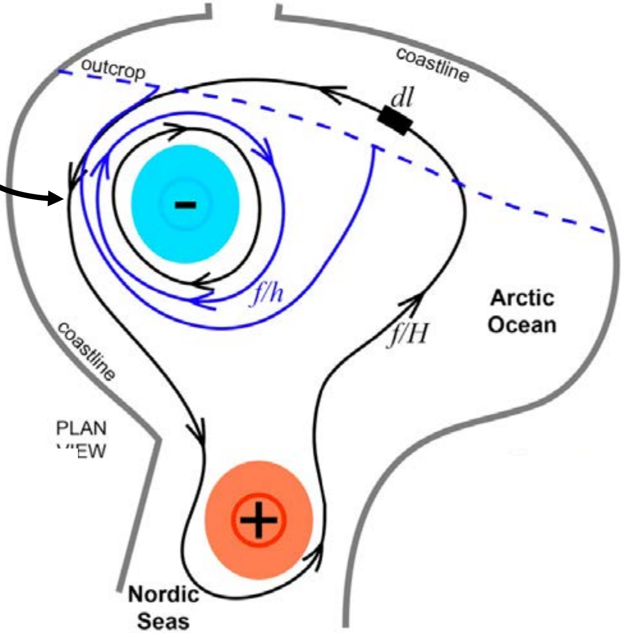
Review in Timmermans & Marshall, 2020

## Conservation of PV:

(Isachsen et al., 2003; Nøst & Isachsen, 2003; Yang 2005; Karcher et al. 2007, 2011; Spall 2013, Dosser & Timmermans 2017)

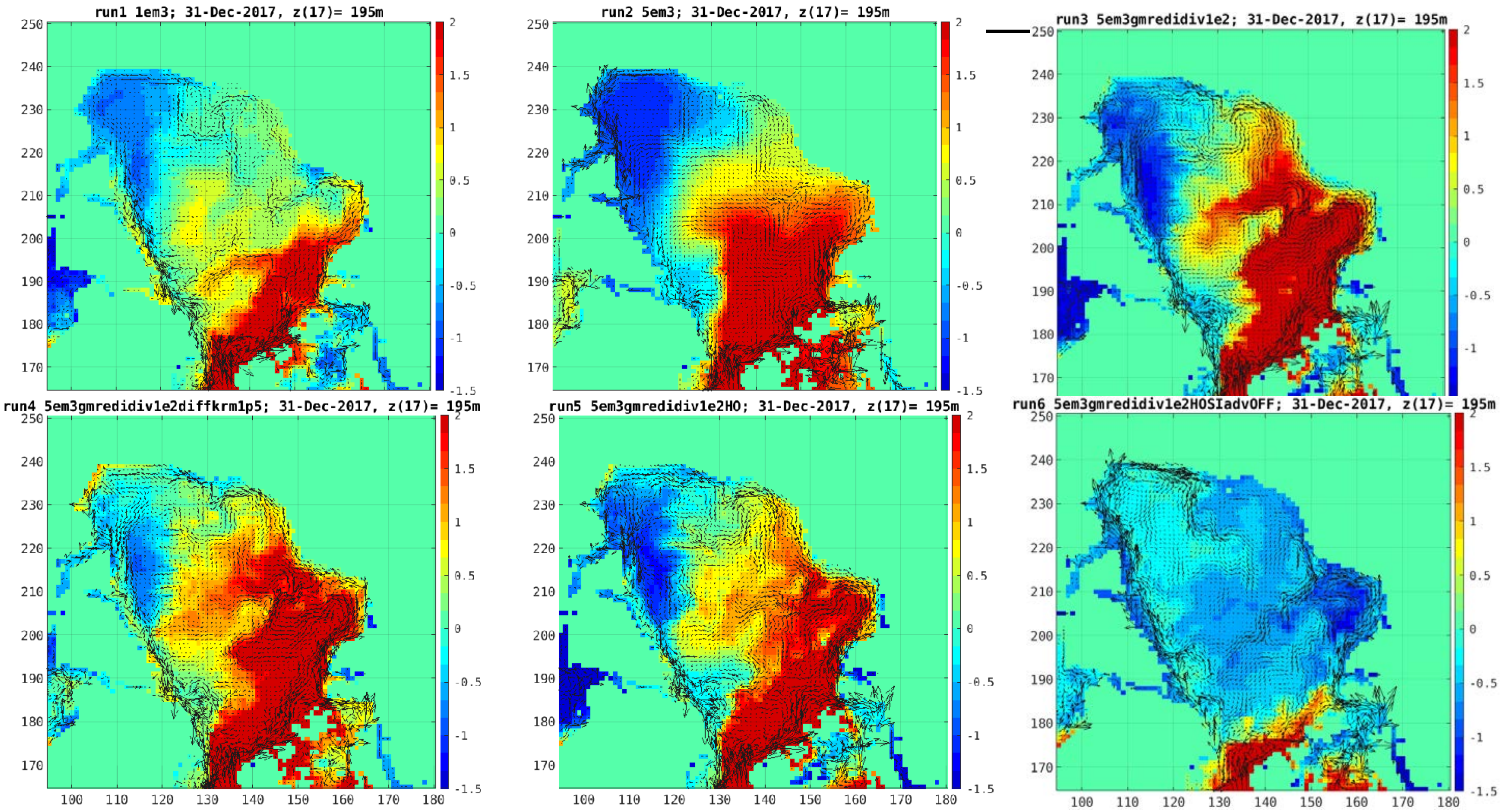
- Closed PV=f/H contour in absence of df/dϕ:
- → **(anti)cyclonic barotropic circulation where area integrated windstress curl is (−)+**
- Balance of Ekman convergence + horz transport + bathymetric drag + dissipation

Potential reversal



# Atlantic Water circulation: Non-uniqueness in an underdetermined problem

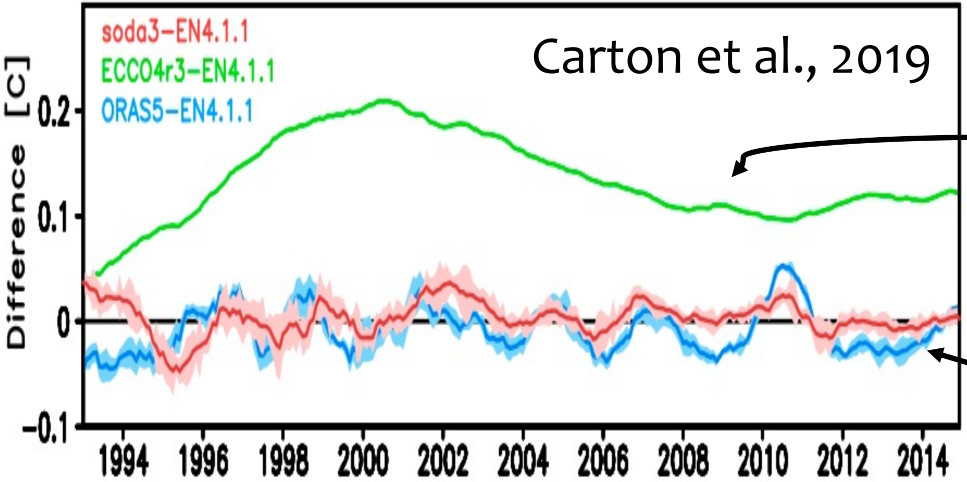




# Consequence of unconstrained parameters:

Model drifts – same in **ALL** models regardless of DA methods

Lessons learned from lower latitudes: when Argo data are not used to **tightly** constrain ODA systems, model trajectories **diverge quickly** from observations within a few **months** (Oke et al. 2015) . In energetic regions, the degradation can occur within **days** (Janekovic et al. 2013).




Nonsequential DA: maps misfit into not-well constrained params along non-unique pathways

Sequential DA: ”fixed” model drifts by re-initialization → Analysis increments (jumps) can be leading term in budget

# Unconstrained inputs: Arctic atmospheric reanalyses

**Graham et al., 2019,**
Evaluation of Six Atmospheric Reanalyses over Arctic Sea Ice from Winter to Early Summer

**Collow et al., 2020,**
Recent Arctic Ocean Surface Air Temperatures in Atmospheric Reanalyses and Numerical Simulations

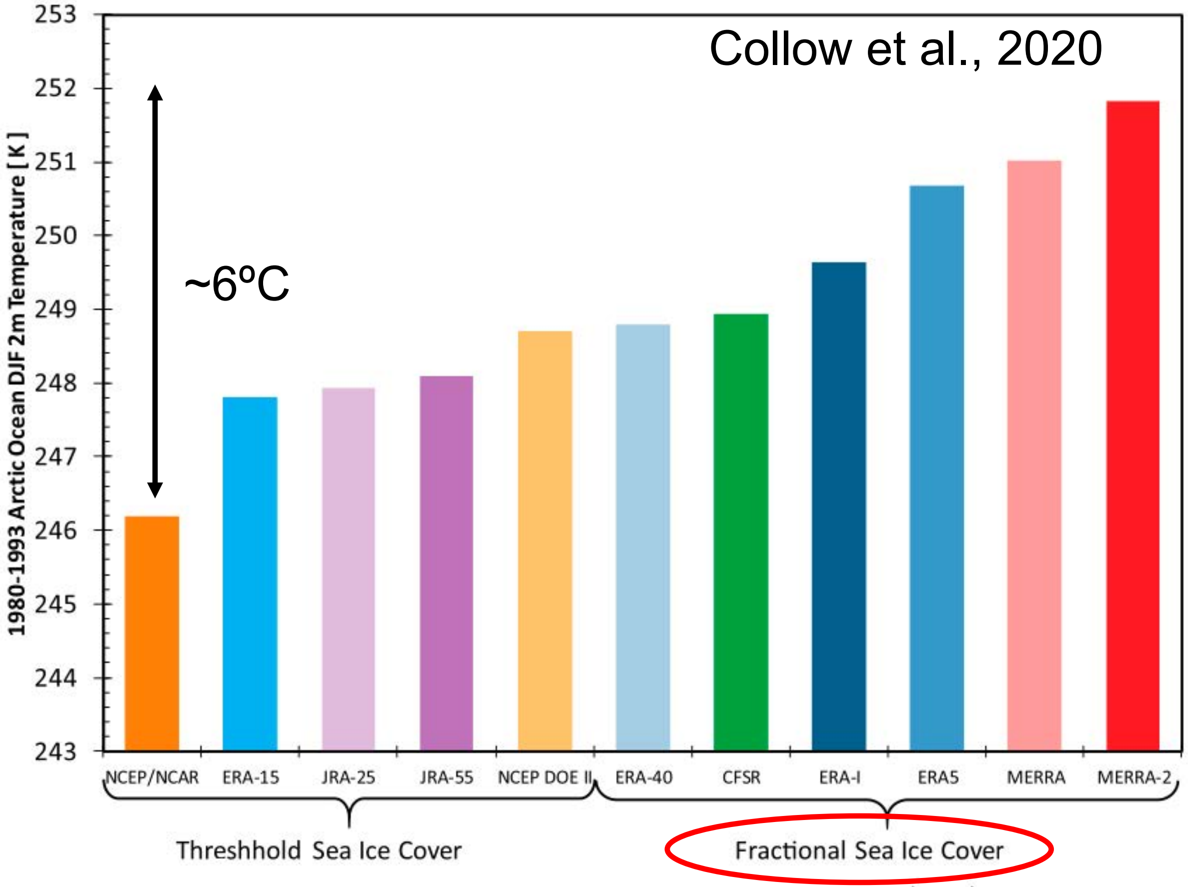



FIG. 6. Averaged Arctic Ocean 2-m air temperatures for winter (DJF) 1980–93.

# Arctic atmospheric reanalyses



Cullather et al. 2016, Systematic Improvements of Reanalyses in the Arctic, IARPC white paper

"Compared to mid-latitudes, the Arctic has a paucity of in situ observations. Additionally, both infrared and microwave satellite sensors have difficulty in profiling the lower atmosphere over snow- and ice-covered surfaces, and geostationary satellites do not cover the high latitudes."

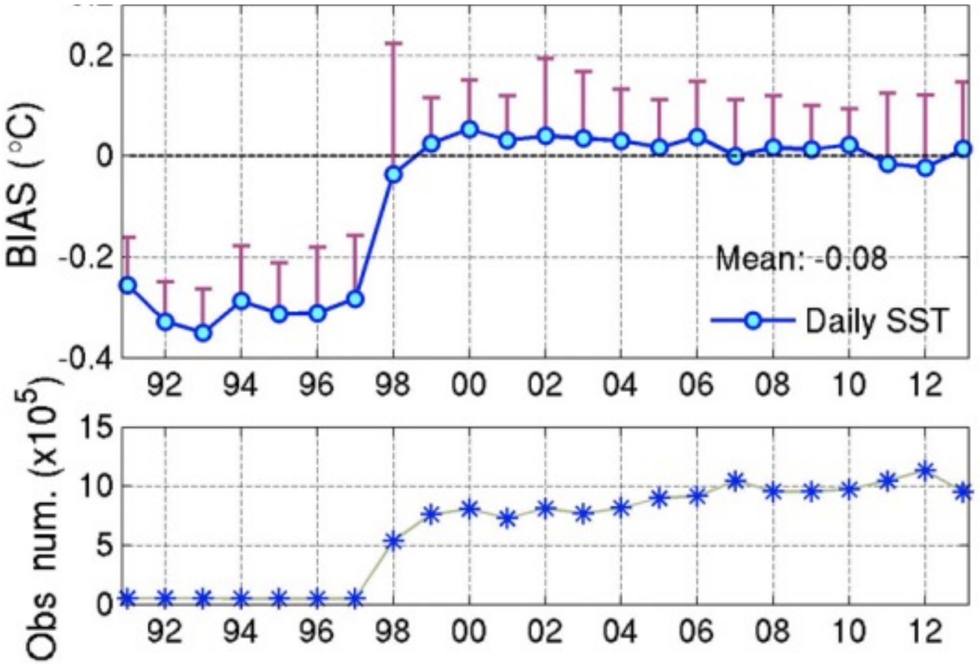
Thus, an atmospheric reanalysis in the Arctic:

- A forward **unconstrained** run (with associated model errors)
- **Trends:** artificial (?) from background forecast (e.g., "trend in time toward larger analysis increment values in MERRA" [Laliberté & Kushner, 2014])

# Consequences of inhomogeneous obs system – Caution in studying “changes”

Artificial temporal / spatial jumps / trends due to data availability

Xie et al., 2017 (TOPAZ4)




Peer-reviewed publication, 2019

“To evaluate bias and accuracy of the reanalyses **only** where observations are actually available…”

“Following the examination of misfits, we explore interannual to decadal variability of global and regional ocean heat content **changes**.”

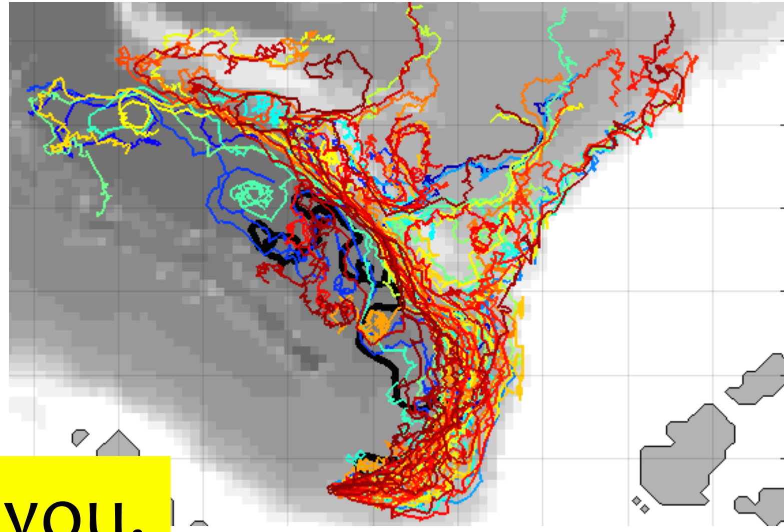
# Future direction: Observational system assessment and design

1. Constraints on parameters relevant to Arctic system circulation:
Parameters that have large impact on model trajectory/drift:
e.g., ocean circulation and mixing, along circulation pathways

2. Identify goals and understand advantage & short-comings of ocean reanalyses
Improve model physics, maintain dynamical consistency? Prediction?

3. Critically assess past, present, and future observational systems:
complementarity, redundancy, carefully designed new system to fill gap (e.g., Loose et al. 2020, 2021)

Nguyen et al., 2020
Arctic Argo floats?



Thank you.

**US CLVAR: Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop,** Seattle, Washington. June 27-30, 2022.

**Objectives**

In recent decades we have seen major changes in Arctic Ocean circulation, salinity, and temperature and associated declines in sea ice coverage and thickness. There is evidence of connections of these changes with climate indices, and the changes arguably affect climate by altering the radiative heat balance at high latitudes, impacting the strength of the global overturning circulation, and influencing the interaction between the ocean and Greenland ice sheet. There are also indications that Arctic sea ice and atmospheric circulation can play an important role in extended range predictability of extreme weather events in mid-latitudes. In spite of its importance, Arctic Ocean observations are limited. Several major in situ observing programs that existed in the 2000s have ended, and today sustained oceanographic observations outside the Canada Basin have almost ceased to exist. This workshop will aim to assess our understanding of the Arctic Ocean circulation and discuss observing system requirements needed to confirm and extend that understanding.

More specifically, the workshop will explore changes in Arctic Ocean and sub-Arctic seas circulation related to global change and the observing system required to track those changes in the future. The observing system design effort will be cognizant of the practical, geopolitical, and operational constraints of Arctic Ocean observing, but will incorporate modern objective experimental design and data assimilation using numerical models as fundamental guiding principles. Its work will contribute to evaluations of model simulations and observational analyses to assess opportunities for model improvements.

**Presentations will address**

A. The state of knowledge of Arctic Ocean and sub-Arctic seas circulation with an eye toward identifying critical gaps in observations of modes of variability

B. The observing system needs and data assimilation approach to track those modes of variability

C. The practical, institutional, technical, and geopolitical challenges of increasing the coverage of Arctic Ocean observations that are required by A) and B)

**Target Participants**

Attendance is open to all, with participation sought from the following communities:

(1) Observationalists (in situ and remote sensing) who are focused on the circulation of the Arctic Ocean and sub-Arctic seas; (2) Data assimilation experts and modelers with an interest in estimating and predicting circulation in the Arctic Ocean and sub-Arctic seas; (3) Investigators and early career scientists with interest in understanding the mechanisms driving variability and change in Arctic Ocean and sub-Arctic seas circulations and relation to climate indices

**Workshop Format**

The 3.5-day meeting will consist of plenary sessions comprised of invited overview summary talks, breakout sessions, and discussion covering three topics: a) the state of knowledge of Arctic Ocean and sub-Arctic seas circulation, b) the observing system and data assimilation needs to track circulation variability, and c) the practical, institutional, technical, and geopolitical challenges of increasing the observational coverage of Arctic Ocean.

**Outcomes**

Deliverables include: (1) Community building across the physical ocean and ice communities studying the Arctic Ocean and sub-Arctic seas; (2) Consensus state of understanding of the changes in the circulation of Arctic Ocean and sub-Arctic seas and their relation to climate indices; (3) Identification of needs for sustained ocean observations to measure variability and change in Arctic Ocean circulation and approaches for supporting them; (4) Strategy for synthesis of in-situ and satellite measurements with assimilative modeling to estimate the state and evolution of circulation within the Arctic Ocean and sub-Arctic seas; The organizing committee will share results with the broader community through a workshop report.

**Scientific Organizing Committee:** Jamie Morison, University of Washington (chair), Dmitry Dukhovskoy, NOAA NESDIS/NCEI, Alison Macdonald, Woods Hole Oceanographic Institution, Mary Louise Timmermans, Yale University, Patrick Heimbach, University of Texas at Austin

# Consequences of analyses increments

Example: ~2-6°C bias in $T_{air}$

→ forcing Arctic coupled ocean-sea ice Reanalyses:

→Where to map this error/bias in atmospheric reanalysis to?

- "extra" heat sink
- Artificial temporal/spatial jumps/trends related to data availability